Annealing Factor as a Metric for Comparison between SPR-III and Ion Beam Laboratory (IBL)

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Motivation—While the Messenger-Spratt late-time inverse gain degradation[1] is an excellent metric for late-time comparisons among the damage produced by Qualification Alternatives to the Sandia Pulsed Reactor (QASPR) program facilities, many qualification conditions require an understanding of early-time transient annealing results. The annealing factor, defined below, is one example of a metric that is used to capture the early-time transient behavior:

$$AF(t) = \frac{\dfrac{1}{G(t)} - \dfrac{1}{G_0}}{\dfrac{1}{G_\infty} - \dfrac{1}{G_0}} \, .$$

G(t) is time-varying gain measured during and immediately after the irradiation, G_0 is the initial gain, and G_∞ is the final ASTM gain (after annealing at 80 °C for 2 hours). The annealing factor is the ratio of damage at any time to the final stable damage population and is proportional to the effective defect density during the annealing period.

Accomplishment—Here we demonstrate the ability to match the temporal profile and the damage creation rate of Sandia Pulsed Reactor (SPR-III) irradiations using the Si irradiations in the Ion Beam Laboratory (IBL). We will compare a maximum SPR cavity pulse (~4E14 n/cm^2) and a minimum cavity pulse (~1E14 n/cm^2) to comparable Si irradiations. Simulating damage creation rates of a maximum cavity SPR-III pulse requires the use of 4.5 MeV Si (directly targeting, in depth, the base-emitter

junction). We cannot produce enough damage in a single 100 μs pulse using the 36 MeV Si (uniform damage over the active region of the device) beam to match these conditions. For minimum cavity pulse irradiations we can simulate SPR-III using either the 4.5 MeV or the 36 MeV Si beams.

Figure 1 compares a maximum cavity SPR-III pulse and a 4.5 MeV Si irradiation, both with 0.22 mA emitter currents. In both cases the duration of the pulse is ~100 μs. The 4.5 MeV Si irradiation condition is chosen based on its 1 MeV silicon equivalent neutron fluence (effectively the late-time ASTM gain values of the two irradiations are the same). We plot the annealing factor as a function of time after the irradiation, shifting the time base so that the peak of the irradiation occurs at t = 0. In Fig. 2 we show a comparison between a minimum cavity SPR-III pulse and a 36 MeV Si irradiation both with 9 mA emitter current. The SPR-III pulse width is ~800 μs, and the transient annealing is masked by late-time gamma/neutron radiation from the reactor. In this example we have not shifted the time base between the two facilities. We conclude that the two facilities produce nearly identical annealing rates.

Significance—We have shown that we can match both the temporal profile and damage creation rate of SPR-III irradiations using 4.5 and 36 MeV Si shots in the IBL for both 0.22 and 9 mA emitter currents. This is critical for the long-term success of the QASPR process, as different device geometries and over-layers will require a variety of ion/energy combinations to simulate the fast burst reactor environment.

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[1] G. C. Messenger and M. S. Ash, *The Effects of Radiation on Electronic Systems*. (Van Nostrand Reinhold, New York, 1986)
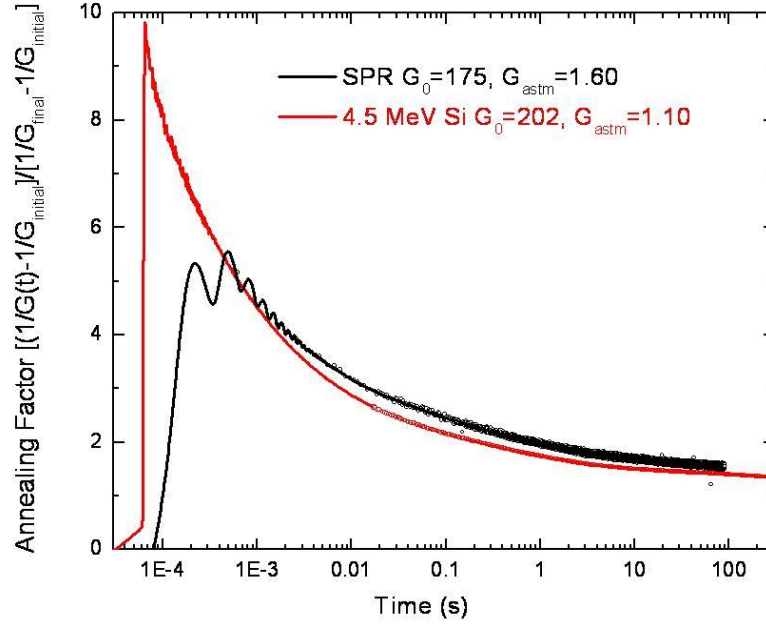
Figure 1. Comparison of a 4.5 MeV Si irradiation (red) and a SPR-III maximum cavity pulse (black), where G_0 is the pre-irradiation gain and G_{astm} is the final gain after ASTM (80 ºC for 2 hr) anneal. This figure displays excellent agreement between the early-time transient annealing between IBL and SPR-III for times $\geq \sim$ 1E-3 s.
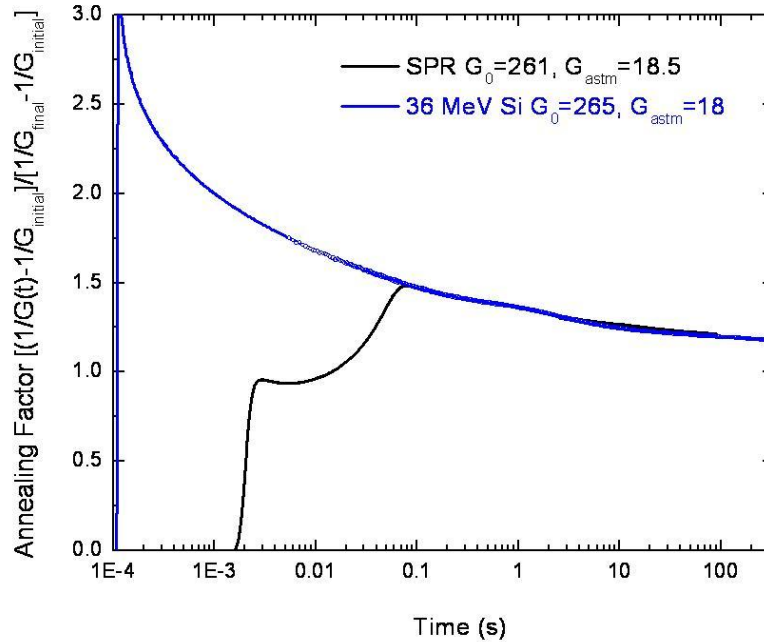

Figure 2. Comparison of a 36 MeV Si irradiation (blue) and a SPR-III minimum cavity pulse (black), where G_0 is the pre-irradiation gain and G_{astm} is the final gain after ASTM (80 ºC for 2 hr) anneal. There is excellent agreement for times $\geq \sim$ 0.1 s after the late-time gamma/neutron radiation from SPR-III dies away.